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Target Considerations for Inner-Shell Photo-Ionized X-Ray Lasing

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Target Considerations for Inner-Shell Photo-Ionized X-Ray Lasing

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Abstract. We present target design for the inner-shell photo-ionization (ISPI) x-ray laser scheme and discuss the requirements for the ionizing x-ray source in rise time and flux. An investigation of the rapid rise time of x-ray emission from targets heated by an ultra-short pulse (USP) high-intensity optical laser was conducted for use as the x-ray source for ISPI x-ray lasing. Modeling using the hydrodynamic/atomic kinetics code LASNEX of a 45 fs USP driving laser with energy of order 1 J incident on a structured Au target composed of vertical rods with diameter of 500 Å predicts sufficient x rays to produce a gain-length product of order 10 in C at 45Å. Collisional ionization to the lower lasing level limits the duration of lasing giving a x-ray laser pulse duration of order 60 fs FWHM. Results of x-ray rise times from instantaneously heated Au rod targets show little benefit in using optical pulse widths less than 15 fs. Our calculations for a constant energy source varying the pulse width show significant increased gain for decreasing pulse widths down to approximately 15 fs. However, for a constant intensity source we see a decrease in gain for shorter pulse widths.

1. Introduction

High intensity ultra-short pulse laser produced plasmas can generate x-ray pulses of high intensity with rapid rise times. These pulses of incoherent x-rays can be used on their own for various applications or as a pump for a x-ray laser [1-5]. In this paper we provide x-ray laser target design and discuss the requirements for the ionizing x-ray source in rise time and flux. The properties of the x-ray source are determined from modeling of a high-Z target heated by an USP driving laser. Gain calculations for C at 45 Å are presented and the driving laser requirements to obtain a gain length of order 10, which is needed to show clear evidence of lasing, are determined.

2. X-Ray Source

Structured targets, as compared to flat targets, have been shown to have larger absorption and greater x-ray conversion efficiency[6]. Research is currently being done on coupling properties of grooved targets by Gauthier, *et al.*[7]. We have previously modeled the emission from such targets assuming absorption in an optical skin depth[8]. Grooved targets, in general, are expensive but easy to model. Cluster targets, e.g., gold-black, are inexpensive but hard to model due to their fractal properties. Work done by Marjoribanks, *et al.* [9] show high x-ray conversion efficiencies in structured targets composed of a two-dimensional lattice of cylindrical absorbers. Modeling of the x-ray emission from these targets, heated by an USP high-intensity optical laser, is performed for Au using the LASNEX hydrodynamic code[10]. The energy is assumed deposited exponentially in an optical skin depth and the atomic kinetics and x-ray emission are calculated with an average-atom atomic model that includes spin-orbit coupling.

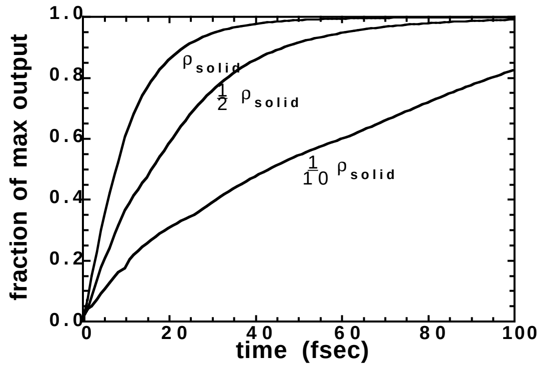

fig 1. X-ray rise time and output in integrated photon energy from Au targets instantaneously heated to 600eV

We first investigate the rise-time limitations of these targets by uniformly and instantaneously heating the rod target (d = 500 Å) to a representative temperature for lasing in C of 600 eV. One can see in fig. 1 that for solid density Au, emission reaches 80% of its maximum value in 16 fs, for half solid density Au, emission reaches 80% of its maximum value in 34 fs and for tenth density Au, emission reaches 80% of its maximum value in 95 fs. Thus in going to shorter and shorter driving laser pulse widths one must be aware that a limit in the rise time of the incoherent x-ray source exists. One would expect little benefit for the inner-shell scheme in C from driving laser pulse widths less than 15 fs. We show that this is the case in the next section where we calculate gain coefficients for various driving laser pulse widths.

3. Inner-Shell Photo-Ionization X-Ray Lasing

The incoherent x rays from a high-Z target, after passing through a low-Z filter, will primarily ionize inner-shell electrons in the lasant. The resulting population inversion lasts for only a short time due to electron collisions which ionize outer-shell electrons [1-5].

For C we find that a 1 J, 45 fs driving laser focused with a width of 10 μm and length 1 cm, incident on a structured target composed of vertical Au rods of diameter 500 Å gives a gain-length product of order 10 for C at a density of 6×10^{19} cm^{-3} in CH_4 (not treating molecular effects) with the resulting x-ray laser pulse duration being 61 fs FWHM at 45 Å. The time dependence of the source intensity is shown in fig. 2a along with the gain coefficient. In fig. 2b, the populations of the upper- and lower-laser states are plotted. From this plot we can see that the upper-laser state population follows the intensity which is expected given the fast Auger exit channel out of the upper state. This will be the case unless the intensity changes on a time scale faster than the inverse of the Auger rate which for C is 10.7 fs. The lower-laser state population grows exponentially due to electron ionization. Since the degeneracy between the lower- and upper-laser states is 1 to 1, the gain goes to zero when the lower-state population reaches the upper-state population.

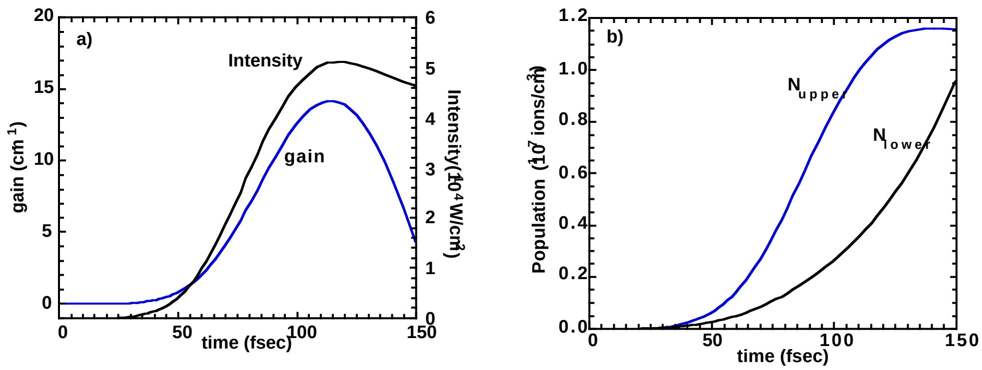

fig 2. The time dependence of the gain coefficient (max 14/cm) in C at 45Å and the source intensity using a 1 J 45 fsec FWHM optical driving pulse is shown in a) The gain profile for C with a density of 6×10^{19} cm^{-3} and the integrated intensity through the filter. in b) The coresponding upper and lower lasant populations.

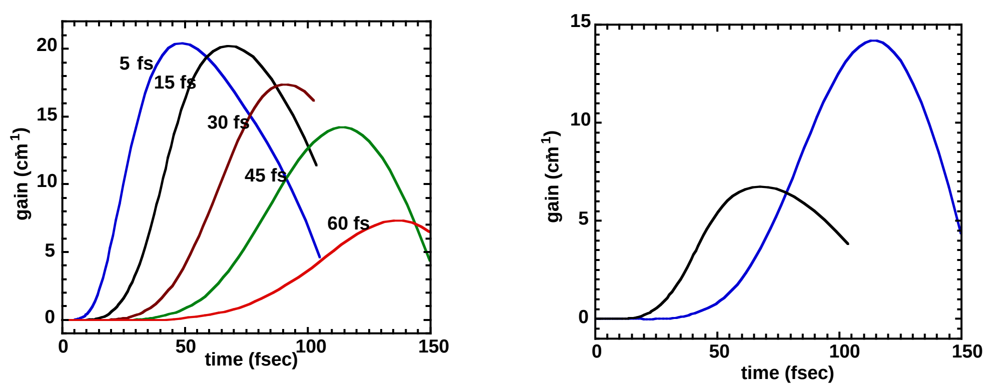

fig 3. An improvement in gain is seen from going to shorter pulse widths with the same energy. In b) a decrease in gain is seen if intensity is held constant.

Given a constant energy source, see fig. 3a, we show the effect on the gain coefficient in changing the pulse duration from 60 to 5 fs FWHM showing an increase in gain of C at a density of 6×10^{19} cm^{-3} from 6 to 16 cm^{-1}. The pump rate to the upper laser level increased by a factor of 2.3. The energy is held constant so the intensity increases as the pulse is shortened. The increase in gain for pulses shorter than 30 fs is modest and we see only a small increase when pulses below 15 fs are used. For a constant intensity of 2×10^{16} W/cm^2,used for 45 fs in the above case, gaves a gain of 14 and 6 cm^{-1} in C respectively for a 45 fs and a 15 fs FWHM optical driving laser pulse. Thus one sees that the energy must be held constant with decreasing pulse duration to achieve high gain.

4. Conclusions

Modeling using LASNEX of a driving laser with energy of 1 J, 45 fs FWHM, incident on a structured target composed of vertical rods (d = 500 Å) is sufficient to produce a large gain-length product. Gains of over 10 cm^{-1} were found for C of a density of 6×10^{19} cm^{-3} using a 4 µm Li filter. Collisional ionization to the lower lasing levels limits the duration of lasing giving a pulse duration of order 60 fs FWHM. Modeling of instantaneous heated targets indicate that rise time limits of the ionizing x rays are on the order of 15 fs. Gain calculations show an increase of gain with shorter duration pump pulses down to approximately 15 fs.

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